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PATENTS

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In re Application of LUTZ AXEL MAY, et al.

Examiner Andre J. Allen

Group 2855

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For: MAGNETISED TORQUE TRANSDUCER ELEMENTS

SUBMISSION OF SUBSTITUTE SPECIFICATION

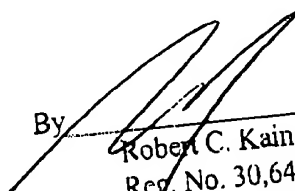
Commissioner for Patents  
Washington, D.C. 20231

Sir:

Applicant hereby submits the attached substitute specification pursuant to 37 C.F.R. § 1.125. The substitute specification compiles the amended sheets submitted to the International Bureau for the PCT and the published PCT application. Amendments to the substitute specification are shown in the enclosed amendment. The revised specification is attached hereto. No new matter is added to the specification.

Respectfully submitted,

By

  
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TITLE: MAGNETISED TORQUE TRANSDUCER ELEMENTSFIELD OF THE INVENTION

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This invention is concerned with to a torque or force transducer based on a magnetised transducer element. The invention relates to a magnetised transducer element and to a method of forming such an element. The invention also relates to a transducer assembly and to a torque sensor system incorporating such an assembly.

15 The invention will be particularly described in relation to transducer elements which are of magnetoelastic material and which are circumferentially magnetised, that is are of an annular form, e.g. circular form, which is magnetised in a closed loop around the annulus. The prior art transducer elements of this type  
20 provide a zero output at zero applied torque which can present a problem in practical applications as will be explained below. However, the invention has wider application to other magnetic-based transducer elements which need not necessarily utilise the phenomenon of  
25 magnetoelasticity in generating a torque-dependent or force-dependent measurement flux. Examples of this more general class of elements are what will be called herein "longitudinal magnetisation" and "radially-spaced magnetisation".

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Longitudinal magnetisation provides an annulus of magnetisation, on a torque-transmitting shaft for example, in which the magnetisation extends in an axial direction at the surface over a defined length and acts  
35 to provide a closed loop of magnetic flux within the shaft. This may be visualised as a torus of magnetic flux. This torus of flux is distorted under torque to provide a torque-dependent tangential component of magnetic field, that is

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a component normal to the radial direction.

Radially-spaced magnetisation is particularly applicable to disc-like parts subject to torque about the disc axis. The disc-like part is of relatively short axial thickness and has two radially-spaced annular zones, e.g. circular in the most common form, which in the limit may be contiguous. The pair of spaced zones are each longitudinally magnetised in the axial direction or each circumferentially magnetised in a closed loop about the axis. In each case a torque-dependent field is generated in a direction which is circumferential to the two zones, that is a field component that is tangential or normal to the radial direction. Transducer elements based on longitudinal magnetisation and radially-spaced magnetisations also provide an output measuring field which is zero at zero applied torque.

Longitudinal magnetisation and radially-spaced magnetisations are described further below. As already indicated, the present invention will be described particularly with reference to the known art of circumferential magnetisation transducer technology as applied to the measurement of torque.

#### BACKGROUND TO THE INVENTION

Transducers of the circumferentially magnetised type are disclosed in related U.S. patents 5,351,555 and 5,465,627 (Garshelis, assigned to Magnetoelastic Devices, Inc.) and in U.S. patent 5,520,059 (Garshelis, assigned to Magnetoelastic Devices, Inc.). These patents describe torque sensing arrangements for a rotating shaft in which a transducer ring or torus is secured to the shaft to

rotate therewith and to have the torque developed in the shaft transmitted into the transducer ring. The ring is of a magnetoelastic material circumferentially magnetised and the flux emanating from the ring due to the stress of the ring under torque is detected by a non-contacting sensor system as a measure of the torque.

Another proposal is described in corresponding PCT application PCT/GB99/00736 filed 11th March, 1999, published under the number WO99/56099 on 4th November, 1999.

In this proposal a shaft of a material capable of exhibiting magnetoelastic material has a portion of it directly magnetised to support a circumferential magnetic field about the shaft axis, an approach which is contrary to the thinking in the prior art. The magnetised portion of the shaft acts directly as the torque transducer element.

To illustrate the operation of a magnetoelastic torque transducer as represented by the above two proposals reference may be made to Figs. 1A and 1B which show a separate ring transducer element secured to a shaft and a transducer element provided by a portion of the shaft itself. The shafts rotate about the longitudinal axis A-A.

In Fig. 1a the shaft 10, assumed to be of circular cross-section, has the transducer ring 12 securely clamped on it by any of the means described in the three U.S. patents mentioned above. The transducer ring 12 supports a circumferential field  $M_c$  extending around the ring. If the shaft 10 is of low magnetic permeability, e.g. paramagnetic, the ring 12 is mounted directly on the outer

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surface of the shaft. If shaft 10 is ferromagnetic, that is of high permeability, a low permeability spacer (not shown) is mounted between the ring and the shaft.

In Fig. 1b, the solid circular shaft 10' is of a magnetoelastic material having an integral portion 12' of it directly circumferentially magnetised to provide the transducer element (the lines delineating portion 12' are notional for clarity of illustration). As employed in previous torque sensors, with the shaft 10 or 10' static and no torque applied, the circumferential field  $M_c$  is entirely contained within the transducer element 12 or 12' so that an exterior non-contacting magnetic field sensor will not detect any field emanating from the transducer element. The application of a torque causes the contained field to skew and the opposite sides of the transducer to be oppositely magnetically polarised (i.e. N-S) to generate a torque-dependent magnetic flux that links the poles externally of the transducer element to enable a magnetic sensor to detect the torque-dependent external field  $M_e$ . It will be understood that this external field forms a torus or doughnut around the shaft. Many different types of magnetic field sensor devices are available and many sensor arrangement configurations of field sensitive devices may be employed. In the instance illustrated in Fig. 1b, the transducer element 12' is preferably axially bounded by circumferentially-magnetised guard regions 14a and 14b, one to each side. These provide respective poles at the interface that are of opposite polarity, i.e. have a repulsive effect, to the poles of the transducer element

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enhancing the emanation of externally detectable magnetic field from the transducer element for measurement of torque. The circumferential fields are induced to extend as deeply into the shaft 10' as possible.

5           Another proposal to enhance the emanation of magnetic flux from the transducer element is to provide the transducer element portion 12" shaft 10" with an integral annular section 16 of raised profile as shown in Fig. 1C, so that the upstanding sides assist in emanating magnetic  
10           flux in an external loop. In contrast to the separate ring 12 of Fig. 1 in which all the field is confined in the ring, the annular section 16 is integral and homogeneous with the underlying shaft in Fig. 1c and the circumferential field extends into the body of the shaft.  
15           This technique and that of using guard regions is discussed more fully in the aforementioned PCT publication WO99/56099. For the purpose of description of the principles underlying the present invention, no account will be taken of the guard regions where they are used.

20           Referring to Figs. 2a and 2b, when the transducer element - 12' is shown as an example, it is equally applicable to separate ring 12 - is subject to torque, a magnetic field  $M_s$  emanates from the transducer for sensing by a sensor arrangement 18 of any desired kind. The  
25           external field has a magnitude proportional to the torque and a polarity dependent on the direction of torque T (CW or CCW) as indicated in Figs. 2a and 2B respectively.

The problem posed to some users of magnetoelastic torque transducer elements of the circumferential magnetic

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field kind discussed above is that at zero torque in the shaft, the magnetic field output from the transducer element is zero. Outputs at or around the zero region are liable to be masked by noise. Another related problem with circumferential magnetisation is calibrating the transfer function of a transducer, particular in checking the long term calibration where a stored magnetic field may change, usually (weaken) over the long term. A means of checking calibration without a lengthy procedure is a desirable feature. The zero output at zero torque is also a problem with transducers employing longitudinal magnetisation and radially-spaced magnetisation. Longitudinal magnetisation has a detectable axial fringe field at zero torque upon which calibration can be based.

15 SUMMARY OF THE INVENTION

The present invention enables the provision of a real measurable output at zero torque with a range of linear measurement of magnetic field output against applied torque. The solution proposed by the present invention is to induce the circumferential field in the transducer element when the element is subject to a torque, a concept that will be referred to as pre-torquing. This is in contrast to prior proposals in which the establishing of the circumferential field in the transducer element is done without torque in the element. This pre-torquing of the transducer element during magnetisation may be also called processing torque.

Yet another aspect of the invention is a transducer assembly comprising at least one transducer element of the invention and a magnetic field sensor arrangement.

A further aspect of the invention lies in a torque sensor system including a signal processing means.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The invention and its practice will be further described with reference to Figs. 3 to 7 of the accompanying drawings in which:

Figs. 1a, 1b and 1c show examples of prior proposals for transducer elements magnetised to have a circumferential field,

Figs. 2a and 2b show an example of the emanated magnetic field for the transducer element of Fig. 1b subject to torques of opposite direction, i.e. clockwise (cw) and counter-clockwise (ccw);

Fig. 3 shows the circumferential magnetising of a transducer element under pre-torque and Fig. 3a shows the magnetising and pre-torque conditions as relating to a cross-section of the transducer element.

Fig. 4 shows a graph of magnetic field output ( $M_z$ ) v. torque (T) for the circumferentially magnetised transducer element of Fig. 3 subject to a pre-torque.

Figs. 5a to 5d show response curves relating to different directions of pre-torquing and circumferential magnetisation;



Fig. 6 shows a sensor arrangement employing two transducer elements subjected to pre-torquing, Figs. 6a-6d graphically illustrating different responses obtainable with the two elements according to the direction of pre-torque and circumferential magnetisation respectively  
5 applied to the elements;

Fig. 7 illustrates one magnetising arrangement for obtaining circumferential magnetisation; and

Fig. 8 is a block diagram of a sensor and processing  
10 circuit providing automatic gain control.

Fig. 9 shows the creation of a zone of longitudinal magnetisation in a portion of a shaft;

Fig. 10a illustrates the toroidal form of magnetic flux in the longitudinal magnetised zone;

Fig. 10b illustrates the toroidal form of magnetic  
15 flux established by a two-step magnetisation process;

Figs. 11a and 11b illustrate the generation of a torque-dependent magnetic field vector component with a longitudinally magnetised transducer element in the absence  
20 of pre-torquing in accord with the invention, with the element under zero torque and under torque respectively and Fig. 11c is a magnetic vector diagram;

Figs. 12a and 12b show a torque-transmitting disc to which the invention is applicable, Fig. 12a showing a view  
25 of one face of the disc and Fig. 12b showing an axial section to which is added the magnetising arrangement for establishing radially-spaced annular zones of magnetisation and Fig. 12c is a magnetic vector diagram; and

Fig. 13 shows a view of one face of a modification of

the disc arrangement of Figs. 12a and 12b for circumferentially-magnetised annular zones.

DESCRIPTION OF PREFERRED CIRCUMFERENTIAL MAGNETISATION EMBODIMENT

5 Referring to Fig. 3, a solid shaft 20 of the kind shown in Fig. 1b is seen being subject to magnetisation  $M_c$  at a portion 22 while under a predetermined torque  $T_0$ . The magnetising method may use a permanent magnet 24 brought up adjacent to the portion 22 of shaft 20 while it is rotating  
10 under the predetermined torque  $T_0$ . A preferred arrangement is shown in Fig. 7. Instead of a permanent magnet, an electromagnet may be used or the shaft subjected to an axially directed current. Various methods are available and some of these are disclosed in the above three U.S.  
15 patents and particularly U.S. patent 5,520,059; and also in above-mentioned PCT publication WO99/56099. Alternatively the shaft may be held static with the predetermined torque  $T_0$  applied to it while a magnet system is moved around it. Magnetisation by an axially directed current is also  
20 applicable to the static case.

Fig. 3a indicates the directions of pre-torque  $T_0$  and circumferential magnetisation  $M_c$  about the axis. The example shown has both of them clockwise. From Fig. 3a, it will be appreciated that there are four magnetising and  
25 pre-torque conditions -  $T_0$  is CW with  $M_c$  being CW or CCW; and  $T_0$  is CCW with  $M_c$  being CW or CCW. These enable different torque response curves to be established as will now be described.

When the circumferential field  $M_c$  is induced in the

presence of torque  $T_0$ , this sets up the condition at which zero external field is produced by the transducer element. When the pre-torque is relaxed so that the shaft returns to a zero torque state, the circumferential field is skewed to  
5 a certain extent resulting in its opposite sides becoming polarised as shown in Figs. 2a and 2b resulting in there being is a quiescent external field  $M_0$  at zero torque.

Fig. 4 illustrates the magnetic field output  $M_0$  available to an external sensor as a measure of torque  $T$  for a given direction, say CW, of magnetisation. The  
10 dashed line in Fig. 4 shows the conventional case without any processing torque or pre-torque during magnetisation. The torque axis of Fig. 4 shows the output field reversing as the torque passes through zero, e.g. as the torque goes  
15 from one direction (CW) to the other (CCW). At zero torque in the conventional case the circumferential field is trapped within the transducer element and there is no external magnetic field available for sensing.

The full line A in Fig. 4 shows the effect of pre-torquing as now proposed. The zero field output is at the  
20 pre-torque value, i.e. at a know predetermined torque, here shown as  $-T_0$  from a CCW pre-torque, providing a working range of torque extending from a negative value to a positive value in which the output field  $M_0$  is of the same  
25 polarity so that there is no signal polarity reversal to cope with in the processing circuitry, and with a real, non-zero, field output  $M_0$  at zero torque lying with a useful range of torque response. It is to be noted that the absolute axial direction of the external flux emanated for

a given direction of circumferential magnetisation differs for different materials.

Fig. 1 shows one of the possible four combinations of circumferential field direction and pre-torque direction mentioned above. Figs. 5a to 5d illustrates graphically the responses due to these four possibilities in a given shaft with clockwise and counter-clockwise directions being defined as in Fig. 3. Figs. 5a to 5d show a set of line curves of the four responses of detectable output field ( $M_e$ ) v. torque (T) and which may be summarised according to the following table labelled a)-d) in conformity with Figs. 5a-d.

Pre-Torque ( $T_o$ ) Direction	Magnetising Field Direction	Output Field ( $M_e$ ) (Zero Torque)	Response Slope
a) CW	CW	$-M_o$	+ve
b) CW	CCW	$+M_o$	-ve
c) CCW	CW	$+M_o$	+ve
d) CCW	CCW	$M_o$	-ve

It is to be understood that for different materials, the sign of  $M_o$  and the slope may be reversed. However, the outcome is still four responses of the kind shown. These may be combined for plural transducer elements as will now be described. It will also be appreciated that any response can effectively be inverted by the processing of the electrical signals obtained from the magnetic field sensor.

It will be appreciated that the requirements for measurement of torques in shafts depend on the

circumstances in which the shaft is used. For example, it may always rotate in a single direction or it may be required to rotate bi-directionally. Torque sensors may also be applied in circumstances where one end of the shaft  
5 is fixed and the other end is subject to some applied torque to be measured.

It is an important facet of the present proposals to apply the pre-torquing concept to obtain advantageous results from shafts having multiple axially displaced  
10 transducer elements. Fig. 6 shows a shaft 30 having two transducer elements 32 and 34 axially spaced along the shaft but subject to the same torque in the shaft. It will now be explained how an advantageous torque transducer response can be achieved by using two transducer elements  
15 with various combinations of pre-torque and circumferential magnetisation directions. Each transducer element has its output field sensed by a respective sensor arrangement 36 and 38 connected to processing circuitry 40.

One form of magnetic field sensor arrangement, using  
20 saturable inductor sensing elements, and signal conditioning circuitry for generating the output indication signal is that disclosed in published PCT application PCT/GB98/01357, publication number W098/52063.

Fig. 6a shows output responses,  $M \propto T$ , for the two  
25 transducer elements 32, 34 being magnetised and pre-torqued in accordance with conditions 5c) and 5b - opposite polarity circumferential fields of equal strength and equal but opposite pre-torques. There will always be an output from one transducer element even when the other is in the

zero output region. This avoids having to make use of a single low output signal whose signal-to-noise ratio (SNR) may be poor. Fig. 6b) shows output responses,  $M_v T$ , for the two transducer elements being circumferentially magnetised with the same polarity and of equal strength but with equal but opposite pre-torques - Figs 5b) and 5a). These outputs may be combined (summed) at 40 to give a resultant (dashed line) extending through the zero origin but with the advantage that the measurements at or near zero torque will have been made with signals of good SNR.

Figs. 6c and 6d are similar to the conditions of Figs. 6a and 6b but relate to cases where the circumferential fields in transducers 32 and 34 are of different strengths. Still more variations are readily visualized by using different magnitudes of pre-torque. The transducer elements whether they are of the kind integral with the shaft or of the separately attachable ring type have response characteristics established by any of the parameters: direction of pre-torque and its magnitude, and direction of circumferential magnetisation and its strength.

Another important use of these multiple field arrangements as the basis of an automatic gain control or calibration for a torque sensor system. Take, for example, the situation of Fig. 6a. It will be understood that if the two output signals are summed, the sum should be a constant value ( $M_s = 2M_0$ ) at all torques. Over time the circumferential fields may weaken so that if an initial sum value  $M_i$  is stored as a calibration point, the later

obtained instantaneous sum  $M_s$  can be compared with  $M_c$  and used to derive a compensating value to correct later sensor measurements.

5 This compensation procedure can be applied where the two fields are not equal in strength but more computation will be required.

10 In order to better explain the application of automatic gain control or compensation, reference is made to Fig. 8 which shows a block diagram of a sensor and signal processing circuit for an arrangement broadly in accord with Fig. 6 to implement a measurement response of the kind illustrated in Fig. 6b using the inversion of one sensor signal to obtain a reference value such as indicated by  $M_s$  in Fig. 6a. The example to be illustrated has 15 transducer regions 32 and 34 magnetised in accord with the responses of Figs. 5c and 5a respectively, namely, opposite but equal magnitude pre-torques and the same circumferential field direction, and of equal strength.

20 Referring to Fig. 8, it shows an analogue processing circuit 40 for processing the signals from sensors 36 and 38 of Fig. 6. The sensors 36 and 38 are illustrated as single coil sensors 60 and 62 respectively with which is included a respective driver and control circuit and respective buffer amplifiers 64 and 66. The manner in 25 which coil-type magnetic field sensors are employed in transducer systems and a specific circuit for this purpose are disclosed in PCT application GB98/01357 published under the number WO98/52063. Each of the buffer amplifiers 64 and 66 has associated with it a means for adjusting the

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amplifier gain, assumed to be nominally unity, and the amplifier offset. The sensors 60 and 62 have respective voltages  $V_1$  and  $V_2$  induced in them. The sensors are mounted to have the voltages  $V_1$  and  $V_2$  induced in the same sense and  
5 to have any signal due to the earth's magnetic field or other extraneous field induced in the same sense. Thus each of  $V_1$  and  $V_2$  is in practice the resultant of the torque dependent magnetic flux sensed thereby and any extraneous unwanted flux.

10 In one of the sensors, 38, the input signal is inverted so that the buffer amplifiers produce output signals  $V_1$  and  $-V_2$  for further processing. The response curves at this point are now equivalent to Fig. 6a. The circuit 40 comprises a main signal path 70 and an automatic  
15 gain control loop 80. The circuit is designed to combine the signals  $V_1$  and  $V_2$  to provide an output voltage  $V_o$  following the torque-dependent dash line curve in Fig. 6b, i.e.  $V_o = V_1 - V_2$  in the ideal case. It will be noted from Fig. 6b that  $V_1$  and  $V_2$  are of equal magnitude, follow torque  
20 curves of equal slope, one increasing linearly with torque  $T$  from the zero torque point and the other decreasing linearly with torque  $T$  from that point.

In the main signal path 70, the voltages  $V_1$  and  $-V_2$  are applied to inputs of respective summing amplifiers 72 and  
25 74 of equal (unity) gain. Each amplifier has a second input receiving a signal whose derivation is described below. The output of amplifiers 72 and 74 are applied as inputs to an output summing amplifier 76 to provide the output  $V_o$ . Amplifier 76 is a gain controlled amplifier



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having an input 78 for receiving a gain control signal from the gain control path 80.

5 The automatic gain control (AGC) loop includes a difference amplifier 82 to which the voltages  $V_1$  and  $-V_2$  are applied to thereby obtain a reference signal which is a sum signal ( $V_1 + V_2$ ) providing, in the ideal case, a constant value signal across the torque range equivalent to  $M_z$  in Fig. 6a. This sum signal is applied through block 84 to develop a signal at appropriate level to control the gain of summing amplifier 76 in accord with an initialising procedure discussed further below. The action of this forward gain control loop is further described below.

10 The output of difference amplifier is divided-by-2 at 86 and the output is passed directly to a second input of amplifier 72 and via an inverter 88 to a second input of amplifier 74 to re-enter the main signal path.

The operation of the circuit 40 is as follows.

20 The signals applied to the two inputs of amplifier 72 are  $V_1$  and a signal derived from the summation of  $V_1$  and  $V_2$  in the AGC loop 80. The signals applied to the two inputs of amplifier 74 are  $-V_2$  and the same second signal as applied to amplifier 72, but inverted. The signals applied to the inputs of amplifier 76 from amplifiers 72 and 74 are summed subject to a gain control to provide an output

$$V_o = k (V_1 - V_2).$$

25 It is worth noting here that the sensor devices 60 and 62 were so arranged that any induced signal components, such as from the earth's magnetic field were in the same

sense with respect to  $V_1$  and  $V_2$  so that these components will be cancelled from the final output.

The sensor circuits 36, 38 and the processing circuit 40 are initially set up so that the output  $V_o$  represents the  
5 desired dashed line response of Fig. 6b by combining the  $V_1$  and  $V_2$  responses as a function of torque, e.g. the responses 32 and 34 of Fig. 6b.

It will be understood that the compensation techniques discussed above could be implemented in software. For  
10 example, the sensor output signals  $V_1$  and  $V_2$  may be digitised and the functions of the signal processing circuit 40 implemented on the digitised signals using software routines.

One of the potential problems with circumferential  
15 magnetic fields, such as 32 and 34, is that they may weaken over time. Thus for the same torque values, lesser values of  $V_1$  and  $V_2$  will be obtained. The initialising procedure may make use of the magnetisation established under the pre-torque values (Fig. 6b). The sum of  $V_1$  and  $V_2$  at the  
20 sensor buffer output can be identified with a specific torque value -  $2T_o$  - in this example and thus with a torque measurement sensitivity (volts/Nm). The offset and gain (slope) resistors R1 and R2 associated with the sensor buffer amplifiers provide a means of ensuring that the sum  
25 ( $V_1 + V_2$ ) to be used as a reference is constant across the range of torque measurement. Later changes in the summation ( $V_1 + V_2$ ), such as weakening of the transducer region fields, is then compensated by adjusting the gain of amplifier 76 (i.e. the factor "k") by means of the AGC loop

90. This sets the gain or scaling factor of the amplifier  
76. The loop can also act to compensate perturbations in  
the  $V_1$  and  $V_2$  signals during, for example, rotation of a  
shaft whose torque is being measured. This compensation  
5 can be afforded on a real-time basis as the shaft is  
rotating.

The system can compensate for the effect of  
temperature changes on the basic sensor sensitivity. It  
can compensate for changes in the distance between the  
10 magnetic field sensor and the shaft as the shaft rotates.  
Generally, aging effects, e.g. leaching away of the  
transducer region fields will be compensated to maintain  
the initial torque sensitivity.

Reverting to the magnetising arrangement indicated at  
15 24 in Fig. 3, a more preferred arrangement is seen in Fig.  
7 which shows a cross-section through the portion 22 to be  
magnetised. A pair 50 of opposite polarity magnets have  
respective ends 52, 54 adjacent the shaft but a little  
spaced to generate a field between them having an  
20 essentially circumferential direction and through which the  
circumference of the shaft is rotated.

The practice of the invention has so far been  
described with reference to circumferential magnetisation.  
Embodiments will now be described which utilise the above-  
25 mentioned longitudinal and radially spaced magnetisation,  
assuming transducer elements of ferromagnetic material.

#### LONGITUDINAL MAGNETISATION EMBODIMENTS

The nature of longitudinal magnetisation has been  
outlined above. The techniques taught above for a

circumferentially magnetised transducer element are also applicable to a longitudinally magnetised transducer element or a pair of such elements.

Fig. 9 shows how an annulus of longitudinal magnetisation is applied to an integral portion of a shaft. The portion is to provide a transducer element and it at least is of magnetic material. In Fig. 9 a shaft 110 of magnetic material is rotated about its axis so that a portion 152 of it is magnetised by the axially-spaced north-south poles NS of a magnet arrangement 150. This may be conveniently an electromagnetic which enables the magnetisation to be readily controlled. The magnet system may be moved about the shaft. The result of this magnetisation is to produce an annular zone of surface magnetisation 154 as shown in Fig. 10a having NS poles as indicated. It extends as an annulus about the shaft axis having the remanent magnetisation of the same polarity around the axis of the shaft and axially-directed. As indicated, the annular magnetisation tends to form a closed flux path within the shaft interior to annulus 154 so that a toroid of magnetic flux is established about the shaft axis. What is important is the magnetic field detectable exteriorly of the shaft as will be shortly explained.

The toroidal flux concept can be enhanced as is shown in Fig. 10b which shows a surface adjacent annular magnetised zone 154 within which an interior annular magnetised zone 156 of opposite polarity is established. The two zones combine as shown to provide the torus of closed loop magnetic flux. The magnetisation is obtained

by a two-step procedure. Firstly a deep annular region of the polarity of zone 156 is formed by the magnet 150. Then the surface adjacent zone 154 is formed by reversing the magnetisation polarity of surface adjacent region of the deep region.

Turning to the practical utilisation of the resultant transducer element, reference is made to Fig. 11a which shows the magnetic field of zone 154 as seen at the surface of the shaft in the absence of torque. The arrow  $M_f$  indicates a fringing field which will extend generally in the axial direction between the poles of region 154 in the ambient medium usually air.

Fig. 11b shows the effect of putting the shaft, and thus transducer element portion 152, under torque in one direction about the axis of shaft 110. The longitudinal field in zone 154 is skewed as shown by the arrows (the skew is exaggerated for clarity of illustration). The external fringing field is likewise skewed or deflected as represented by magnetic vector  $M_f'$  (Fig. 11c). Also generated is a vector component  $M_s$  which in this embodiment extends circumferentially about the circumference of shaft 110. The component  $M_s$  is tangential to the shaft at any point, that is perpendicular to the local radius. It is the  $M_s$  component that provides the component for measuring torque by means of an appropriate oriented magnetic field sensor or group of sensors.  $M_s$  is a function of torque. If the torque is in the opposite direction the direction of  $M_s$  is reversed. At zero torque,  $M_s$  has a zero value. This results in the same problem as already described for

circumferential magnetisation, namely the difficulty of measurement at zero or near zero torque.

The solution adopted is the same as for circumferential magnetisation, namely that of pre-torquing the shaft portion 152 while establishing the magnetisation of it so that on allowing the shaft to relax to zero torque, the quiescent field is skewed with a detectable  $M_s$  component. This technique can be extended to more than two longitudinally magnetised regions as taught above in respect of circumferentially magnetised regions.

#### RADIALLY-SPACED MAGNETISATION

The principles given above can be applied to radially-spaced magnetisations which find particular, though not exclusive, application in torque transmitting discs.

Figs. 12a and 12b show a face view and an axial section of a disc 210 which is mounted on a shaft 220 for rotation about its axis A-A and carries, for example, a gearing 224 at its outer periphery for enabling transmission of torque through the disc. Also shown is the provision of a magnet system comprising magnets 216 and 218 on opposite sides of the disc to establish two magnetised zones 212 and 214. Each zone is established as an annulus about the axis A-A, as by rotating the disc between the magnets. Each zone is longitudinally magnetised in that the magnetisation extends in the axial direction and the two zones 212 and 214 have opposite polarities of magnetisation. The two magnetised zones provide a transducer element 222 (the magnets 216, 218 being removed) which from face 211, say, appears as in the

segment of the disc shown in Fig. 12a. At the surface 211 zone 212 provides an annular pole (N) of one polarity and zone 214 an annular pole (S) of the opposite polarity between which an exterior magnetic flux  $M_r$  (Fig. 12c) is established to link the poles. The exterior magnetic field vector is radial at any point around the annuli. Under torque the vector is deflected or skewed from the radial to a position  $M_r'$  to provide a circumferential or tangential component  $M_s$  which extends around the annulus.  $M_s$  is a function of torque having a zero value at zero torque unless the teachings of the present invention are adopted. Thus as in the earlier described embodiments, the magnetised zones 212 and 214 are established while torque is applied (pre-torquing) so that a detectable value of  $M_s$  is generated when the disc is relaxed to a zero torque state.

Fig. 12a also shows sensors 228a-228d for detecting the circumferential component  $M_s$  and sensor 226a-226b for detecting the radial component  $M_r$  used as a reference.

Fig. 13 illustrates how the disc-like torque transducer assembly can be adapted to work with circumferential magnetisation. Fig. 13 is a face view of a disc 350 through which torque is transmitted between a drive applied on the axis A and the periphery or vice versa as previously described. In this embodiment, there is a transducer region 352 which comprises an inner annular region 354 and an outer annular region 356. The regions 354 and 356 have opposite polarities of magnetisation as indicated by the respective arrows. The circumferential